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The application of CFD in the assessment of the patency of the upper respiratory tract

Zastosowanie CFD w ocenie drożności górnych dróg oddechowych

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ABSTRACT: Computational Fluid Dynamics is a rapidly developing instrument with a number of practical applications. CFD simulations have been used for years in aerodynamics, engineering, hydraulics, meteorology, construction, and many other fields. In medicine it was used primarily in pulmonology and cardiology, the areas in which the dynamic properties of the gas and liquid play an important role in the proper functioning of the body. In laryngology, Computational Fluid Dynamics (CFD) is a useful method, which allows calculation and visualization of the changing parameters of air flow in the upper respiratory tract.

KEYWORDS: computational Fluid Dynamics, air flow, larynx

STRESZCZENIE: Obliczeniowa dynamika płynów (CFD) to szybko rozwijająca się dziedzina nauki, mająca szereg zastosowań praktycznych. Od lat używana jest w aerodynamice, inżynierii, hydraulice, meteorologii, budownictwie oraz wielu innych dziedzinach. Pierwsze publikacje dotyczące użycia CFD w medycynie dotyczyły przede wszystkim pulmonologii i kardiologii, czyli dziedzin, w których dynamiczne właściwości gazu i płynu odgrywają ważną rolę w prawidłowym funkcjonowaniu organizmu. W laryngologii CFD umożliwia pomiar oraz wizualizację dynamicznie zmieniających się parametrów przepływu powietrza w górnych drogach oddechowych.

SŁOWA KLUCZOWE: obliczeniowa dynamika płynów, przepływ powietrza, krtań

INTRODUCTION

A review of imaging modalities that may be conducted at the beginning of the 21st century demonstrates a remarkable humility and appreciation for the discoveries of the 19th century, as well as for incredible technological advancements and diversity of current techniques.

A laryngeal mirror, which was first used by Manuel Garcia in 1851 and was in fact a dental mirror, is a basic tool for laryngeal examination used in laryngological practice to this day [1]. Similarly, an endoscopic set for laryngeal examination remained irreplaceable so far. Technological development complemented the diagnostic methods with new imaging modalities and tests used in everyday laryngological practice. The era of imaging studies, such as CT, MRI, PET, videostroboscopy and functional tests, such as EMG, spirometry, or plethysmography, brought incredible precision to patient qualification to surgical treatment or even planning of conservative therapy.

Medicine is open to novelties from the world of industry, engineering and new technologies. Even though we have methods at our disposal that were unreachable several dozen years ago, we are still searching for new diagnostic, imaging and testing possibilities. Computational fluid dynamics (CFD) is a tool used primarily in the field of engineering until recently.

Computational Fluid Dynamics (CFD)

CFD is a domain of fluid mechanics. Fluid mechanics is a branch of physics dealing with movement, fluid balance, as well as forces that affect them: gravity, viscosity, density, and pressure.

The concept of fluid encompasses liquids and gases, which, unlike the solids, are characterized by inability to maintain shape. In the absence of free liquid surface and when gas compressibility does not have to be taken into consideration, the equations of fluid mechanics for liquid are the same as for gasses [2]. The Navier-Stokes equation is the fundamental equation expressing the law of conservation of mass and momentum for moving fluid. Due to the level of complexity the Navier-Stokes equation may be solved analytically only in the simplest cases involving smooth, laminar flow, which occurs rarely, especially under the conditions of a human body. In more complex cases the equations may be solved using CFD.

The complexity of problems related to fluid mechanics is the cause why few practical issues find an analytical solution. For that reason experimental testing is important for verification of calculations. Analysis of even the most complicated phenomena through modeling enables their visualization and allows confronting the results with numerical data.

CFD technique involves developing models of mathematical processes based on the equations of conservation of mass and momentum for moving fluid and finding numerical solutions using computers. Numerical methods are a way of solving mathematical problems using operations on numbers in cases where a given problem does not have an analytical solution, i.e. defined by equations, or it cannot be solved due to its complexity. The obtained result is approximate and its exactitude may be precisely determined [2,3]. After solving the equations that express fluid flow it is possible to approximate velocity, pressure and resistance distributions [2].

CFD computer simulation is conducted in two steps. The first step involves determination of a geometrical model of the vessel, through which flow will take place, while the actual flow simulation is conducted in the second step. Proper computer software is necessary in both stages.

Creating a geometrical model involves transferring values that correspond to appropriate vessel margins onto a 3D coordinate system and determining constant values for the entire vessel, as well as establishing variables, such as pressure and velocity that will be intercalated at the vessel inlet. Second stage involves simulation of flow through the generated geometrical model, where the parameters relevant for fluid flow, such as velocity, viscosity and pressure will be determined. Correctness of the introduced data and the geometrical model is checked multiple times at various stages of simulation. The final result is also an outcome of numerous calculations, performed until they reach a result encumbered with permissible error pre-specified by the researcher. The solution determined using CFD modeling takes graphic and numerical forms. Velocity, pressure or other values required depending on the analyzed problem might be identified for each point contained in the body of the geometric model. All data is also depicted graphically by means of local distribution fields for velocity, pressure, etc. (Fig 1).

CFD computer simulations have been used for years in aerodynamics, engineering, hydraulics, meteorology, construction, and many other fields. Basic principles of computational fluid dynamics were established in the 1930's. Due to high level of complexity of the equations it evolved together with increasing computing power [4].

CFD as a tool in medical diagnostics

For the past two decades the CFD method has been developed in a medical field. Lack of widespread application of this method may be related to its complexity and poor availability. Previous studies involving CFD concern primarily disorders and problems in the fields of cardiology and pulmonology, where dynamic gas and fluid properties are of paramount importance to proper functioning of the organism. In laryngology CFD may be an alternative to actual tests, which might be difficult to perform and would require invasive procedures. Information regarding presence and degree of obturation, as well as its impact on fluid flow is important in all of those fields. In cardiology, coronary angiography constitutes a more easily available and more commonly used, although invasive alternative to CFD. There are no similar tests simultaneously visualizing airflow and dynamics of parameter change in pulmonology and laryngology.

Geometrical model of the studied organ may be constructed with the help of imaging studies: CT, MRI, USS. Use of CT and MRI allows creation of a model that reproduces the organ very precisely. Ultrasound scan may be helpful in the construction of a model that will be used to study isolated flow over a short distance, e.g. through a valve or glottis. This stage of studies requires providing physicochemical properties of the vessel/organ and the fluid. Due to the limitations of computer software, which does not have access to material corresponding to human tissue, such as vascular wall, bronchus or blood, some assumptions should be made. The

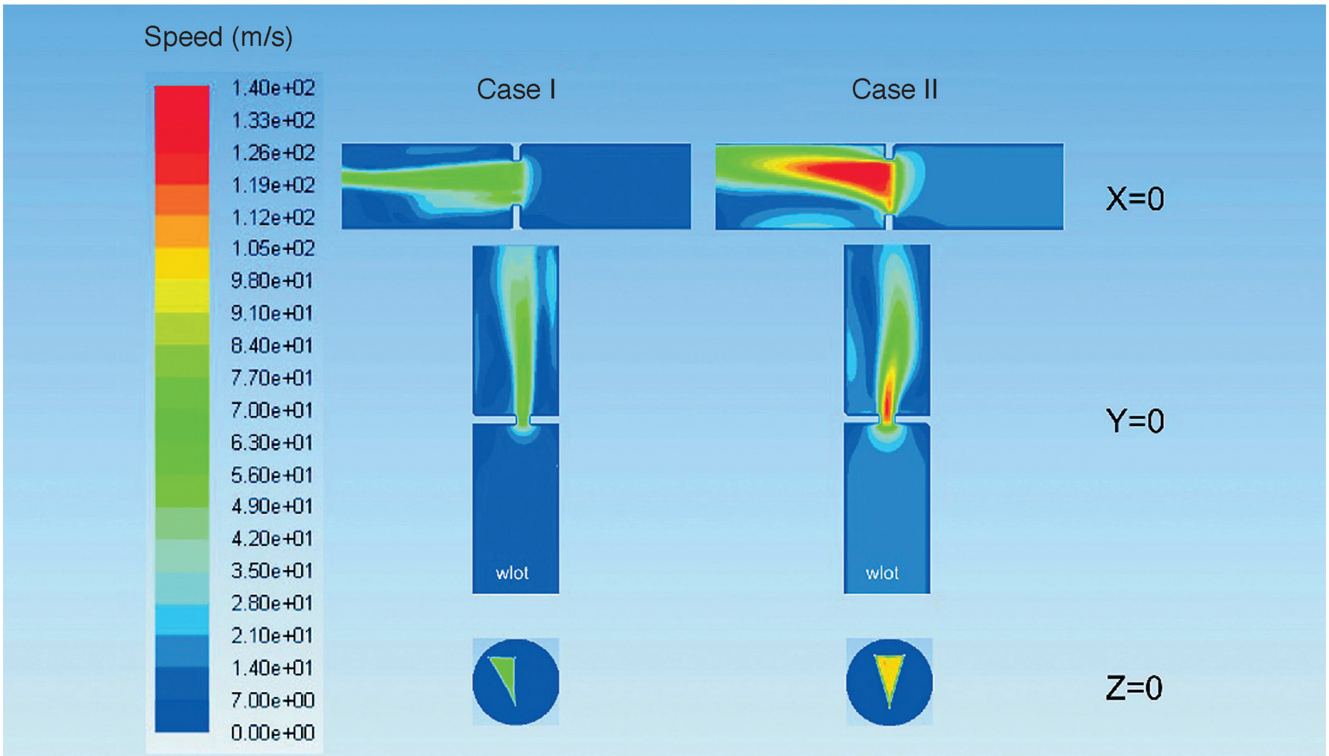

Fig. 1. Comparison of air flow velocity areas between a patient after right-sided partial arytenoidectomy with posterior cordectomy because of bilateral vocal cord paralysis (Case I) and a healthy person (Case II).

data concerning flow, i.e. velocity or pressure, may be acquired from functional tests, such as spirometry and plethysmography for the respiratory system, or Doppler ultrasound for modeling of flow in the cardiovascular system.

CFD computer simulation was repeatedly used in laryngological research studies to visualize airflow in the respiratory tract. Particular attention is paid to analysis of issues related to airflow, velocity and pressure distribution, or distribution of aerosols in the nasal cavity. Tan et al. presented a study of airflow visualization in the nasal cavities of healthy individuals vs. patients affected by obstructive sleep apnea syndrome (OSAS). Geometrical model was created using CT examination with subsequent airflow analysis. It was shown that the resistance created by the tissues of soft palate exerts the greatest influence on the severity of OSAS symptoms. The study was simplified, as the properties of nasal mucosa and soft palate were not taken into consideration. However, it provided basis for further deliberations [5,6]. Zhang et al. used CFD simulation to compare the pressure in the nasal cavity with mean pressures at three levels of the throat, yielding a strong correlation. They noted that negative pressure created in the throat makes it susceptible to collapse and obstruction. The fact that this negative pressure is generated by resistance forces occurring in the nose makes it responsible for pathogenesis of OSAS [7]. Luo et al. conducted a study assessing improvement in the quality of sleep among obese children with OSAS after adenotonsillectomy. Geometrical model was created based on MRI examination [8].

Tian et al. analyzed the distribution of aerosols in intranasal application, while Achilles et al. used CFD in order to demonstrate constricting action of intranasal steroids and oral anti-allergy medication in a group of patients with allergic rhinitis [9,10].

Other studies use CFD to show pathophysiological changes and their consequences in cases of nasal septum deviation, hypertrophy of nasal conchae, nasal bone fracture, and septal perforation [11,12,14,16].

There were only several reports of CFD analysis of the larynx in the literature. Sidlof et al. undertook aeroacoustic analysis of the mechanism of voice generation [15]. Liu et al. proposed a study using CFD method to predict the effectiveness of surgical treatment of OSAS, while Yu et al. correlated the throat geometry and CFD flow with AHI, obtaining good results and indicating their model as useful in clinical assessment [15,16]. Göckan et al. analyzed laryngeal airflow among patients subjected to posterior cordectomy due to bilateral vocal fold paresis [17].

CONCLUSIONS

Regardless of the studied biological system CFD makes it possible to investigate phenomena that are inaccessible to human eye. Despite simplifications, which had to be assumed due to insufficient adjustment of the existing software to studying processes of the human body, acquired results are incredibly precise and impossible to obtain by any other available method. The complexity of this technique is the reason why it is not likely to be used universally. However, experimental studies may set new directions that could possibly be helpful in the diagnostics and planning of treatment of the above-mentioned disorders.

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